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Optimizing Design of Stand-alone Hybrid Solar Micro-CHP Systems using LUS Based Particle Swarm Optimization Algorithm

F. Rashidi*
Assistant Professor

H. Rashidi†
Instructor

Utilizing the combined cooling, heating and power generation (CHP) systems to produce cooling, heat and *electricity is growing rapidly due to their high efficiency and low emissions in commercial and industrial applications. In conventional CHP systems the deficit of the system power can be purchased from the grid. However, this system cannot be used as the standalone application. The hybrid solar micro-CHP system can be worked as a standalone system for remote areas and other places which the access to grid is hard and costly. In this paper, by using energy and economic analyses, the type and the number of the required microturbines for the specific electricity and heat load curves during a year are selected. For performing this task, maximizing the actual annual benefit of the system is considered as objective function. Then, particle swarm optimization (PSO) algorithm and local unimodal sampling (LUS) technique is developed to calculate the type and number of prime mover and also the area of photovoltaic panels.*

Keywords: Microturbine; photovoltaic panels; annual profit; CHP; PSO algorithm; LUS technique.

1 Introduction

CHP system is one of the most important solutions for energy optimization in modern countries. Because of its high efficiency, economical and environmental benefits, it is considered all around the world in recent years [1]. As the power and heat are generated simultaneously in CHP system, the energy productions are increased and utilization of energy resources are optimized [2]. Among different options as prime movers like microturbines, internal combustion engines, gas turbines and steam turbines, microturbines are the most preferred option because of their higher reliability, better performance and lower maintenance requirements [3]. Microturbines are small gas turbines which can work with different types of fuels like natural gas, gasoline and jet fuel to simultaneously provide hot water and generate electricity for buildings [4].

*Corresponding Author, Assistant Professor, Faculty of Engineering, University of Hormozgan, Bandar-Abbas, Iran rashidi@hormozgan.ac.ir

†Instructor, Faculty of Engineering, University of Hormozgan, Bandar-Abbas, Iran halimeh_rashdi@yahoo.com
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Micro-CHP system is a special type of distributed generation systems which is suitable for different civil and industrial applications, such as residential buildings and hospitals [5]. Micro-CHP systems maybe integrated with the renewable energy sources such as solar and hydrogen [6]. Among renewable energies, photovoltaic (PV) systems are particularly suitable for stand-alone applications due to availability and potentiality of solar sources [7]. Recently, a number of studies have been reported in various aspects of micro-CHP systems such as performance assessment and economic analysis. Ref. [8] investigates the lowest cost operating strategies for three micro-CHP systems based on stream engine and gas engine, each capable of producing a power output of 2kW under reasonable estimates of energy prices. Ref. [9] proposed a new objective function annual profit to select the appropriate number and type of drivers for a micro-CHP system. The objective function is calculated for electricity and heat curves during a year. In [10] the operation of biomass based micro-CHP system is optimized subject to maximizing the economic index in the form of modified internal rate of return. In [11] an integration of PV based micro-CHP system is introduced and a new methodology is proposed to provide plant size.

Identifying the optimum sizing of micro-CHP is a major challenge as several parameters must be concurrently considered. In [12] the size of a micro-CHP system with heat storage is optimized using mixed integer non-linear programming method. The optimum sizing of a hybrid micro-CHP and biomass is evaluated in [13] using PSO algorithm. Ref. [14] uses an optimization method based on genetic algorithm for the optimal design of a micro-CHP so the electrical and thermal demands can be cost effectively satisfied. Ref. [15] proposes a method based on mixed integer linear programming and experimental input data for the optimal sizing of a CHP system. In [16] a hybrid PV and micro-CHP system is optimized using non-adaptive linear programming. However, some consideration which can strongly impact the outcomes of any system optimization was not reported. Ref. [17] performs a multi-objective genetic algorithm for a residential CHP system with exegetic efficiency and environmental cost rate as objective functions. The study considered a micro gas turbine and an absorption chiller to meet cooling, heating, and electrical power. In [18] a multi-criteria sizing function to optimize the size of prime movers for a residential micro-CHP system is investigated and thermo-economical and environmental parameters are calculated. However, the dynamic load profile is not considered. Because of the complexity and nonlinearity involved in optimal sizing, some intelligent optimization algorithms such as genetic algorithms [19], differential evolution algorithm [20], and particle swarm optimization [21] have been extensively used for CHP system optimization. Due to the large numbers of parameters in CHP optimization problem, the use of an efficient and global optimization algorithm is essential for optimal design of the system.

Although literature review shows that evolutionary algorithms, especially genetic algorithms provide quite good results in the field of trigeneration system optimization, in order to fill the existing gap in optimization of the hybrid micro-CHP and PV system and also increase the variety of available tools, other alternatives of optimization techniques shall be taken into consideration as well. The main objective of this paper is to present an optimization methodology that could help to improve the hybrid PV and micro-CHP design using hybrid LUS and PSO algorithm. Major contributions of this research are as follows:

- To model a stand-alone system consisting of solar, microturbine and micro-CHP.
- To perform energy and economic analyses of this system.
- To propose and apply an optimization algorithm based on PSO and LUS technique.
- To calculate the type and number of prime mover and also the area of photovoltaic panels.

2 Energy System Configuration

The conceptual design architecture of the proposed hybrid energy system is shown in Figure (1). As can be seen from this figure, the considered system is made up of a PV device; a micro-CHP system which includes, microturbine, boiler and natural gas tank.
The main part of microturbine is compressor, combustion chamber, turbine and generator. The source of thermal energy in micro-CHP systems is the hot exhaust gas from combustion. The temperature of exhaust gas is about 400-600°F which can be used for producing hot water or low temperature steam related to our needs [3]. As the CHP system is located near the consumption place, the losses of energy in transmission path are neglected. There are different procedures to analyze the CHP systems; however, two of them are more important, return of investment and maximum annual profit. In this paper both of them are considered for selecting the type and number of microturbines. To achieve this, an objective function is developed and the cost of power and heat are determined. Costs are formulated such that any increase in power loss leads to increase in costs.

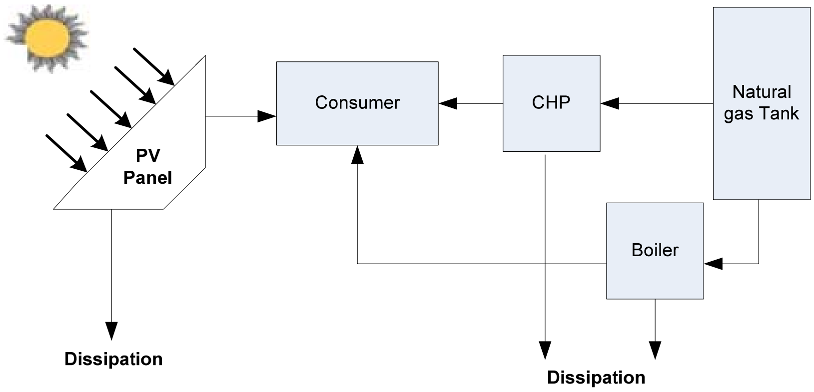

Figure 1 Block diagram of the hybrid system

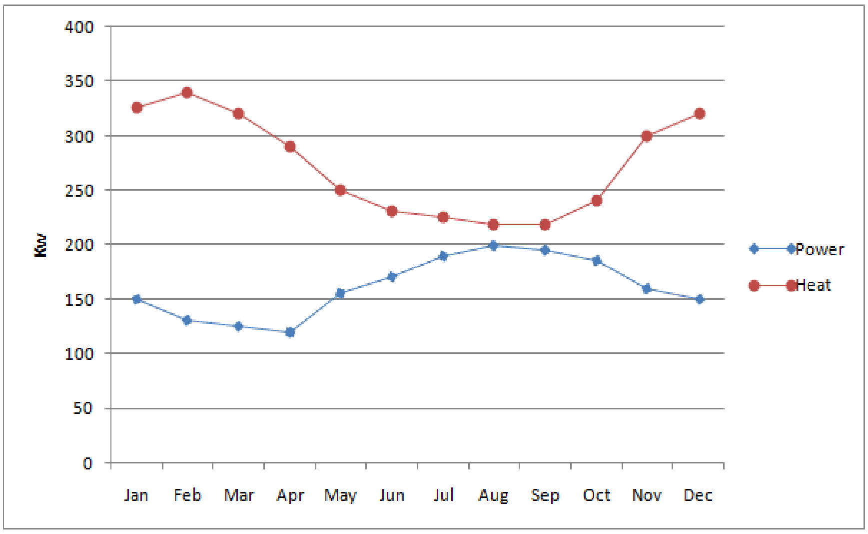

Figure 2 The required electricity and heat loads

3 Assumption and system description

Before optimizing the system and introducing the objective function, it is required to evaluate the heat and power load profiles, type of commercial microturbines to generate heat and power and solar power availability to supply deficit load using PV panels. In the first step, the heat and power load profile that system should supply is determined. The hourly meteorological data of Kerman city, Iran are used for simulation as shown in Figure (2). The meteorological data and yearly load profile remain constant over the planning horizon [22]. As shown in this figure, the maximum value of heat and power load is 340kw and 200kw, respectively. The second step is related to the specification of the microturbines as the prime mover for the micro-CHP system, Table (1) presents the characteristics of 5 types of some market available microturbines which are investigated in this paper [22]. As the previously mentioned, the deficit load of system is supplying by PV panels. The PV panels used in this paper are made by Crystalline Silicon and their efficiency for converting energy from solar power into direct current is about 16%. The investment costs of these commercial panels are shown in Table (2) [23]. The solar power is directly related to weather conditions.

Figure (3) shows the variations of daily average radiation on the surface area over a year [24].

Table 1 Specification of selected microturbines [22]

Systems type	Manufacture	Model	W(kw)	$\eta_p(\%)$	$m_G(\frac{kg}{s})$	$T_{ex}(°C)$	$P_f(psi)$
A	Capstone	Model330	30	26	0.31	275	55
B	Capstone	60ICHP	60	28	0.49	305	75
C	IR energy system	70LM	70	27	0.73	232	70
D	Honeywell	Parallon75	75	25	0.68	260	65
E	Elliott	TA80	80	28	0.74	280	70
F	Turbec	T100	100	30	0.8	271	80

Table 2 The cost of the PV panels [23]

Price, average value (modules)	$ per watt
Total Modules:	0.45$
Crystalline Silicon	0.51$
Thin-Film	0.28$
Concentrator	0.47$

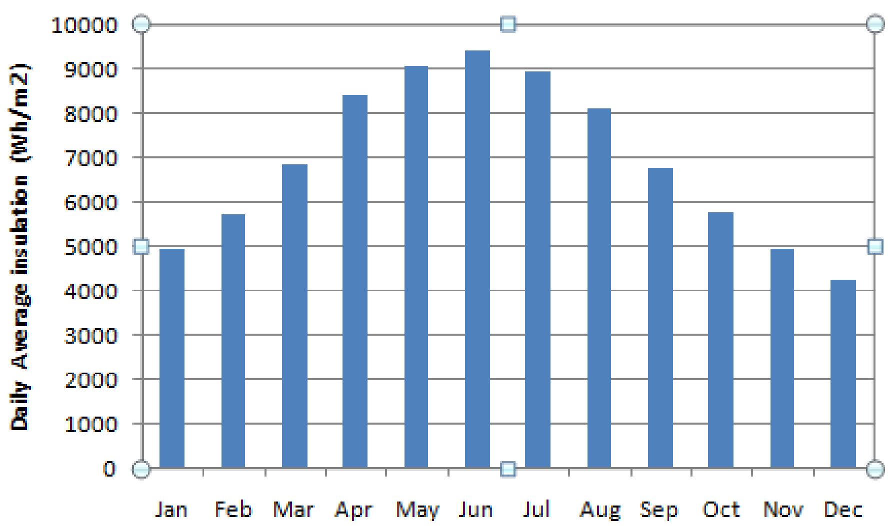

Figure 3 Variation of daily average radiation

4 System Modeling and Analysis

Microturbine is a small size gas turbine operating based on Brayton cycle with about 30% thermal efficiency [6]. According to the thermodynamic cycle and considering all inputs and outputs, the flow of microturbines that shown in Figure (4) can be analyzed using energy equation. The electrical energy (E_e), thermal energy of hot gas (E_{hG}), thermal energy of domestic hot water (E_{hW}) and fuel energy (E_f), can be calculated using following equations. Electrical power energy is calculated according to the generator's power and efficiency as follows [24].

$$\dot{E}_e = \eta_{GEN}\dot{W} \tag{1}$$

According to the results presented in the literature, the efficiency of generator is about 97 percent. Thermal energy of hot gas is related to the flow rate and enthalpy of flow line in heat exchanger, by considering ideal gas mixture, the temperature of stack is greater that dew point and is in the range of 51.6 to 65.5 centigrade degrees [24]. Hence,

$$\dot{E}_{hG} = \dot{m}_G(h_{HG} - h_S) \tag{2}$$

Thermal energy of domestic hot water (E_{hW}), can be calculated as the thermal energy of hot gas (E_{hG}),

$$\dot{E}_{hw} = \dot{m}_w(h_{HW} - h_{CW}) \tag{3}$$

Finally, the fuel energy is related to the flow rate of fuel and also Low Heating Value (LHV) of fuel

$$\text{, LHV=48000 kj/kg}\dot{E}_f = \dot{m}_f \times LHV_f \tag{4}$$

Fuel heat loses is considered to be equal to 5% of fuel energy ($\dot{E}_f$).

The main objective of this paper is to achieve an optimal standalone micro-CHP system. Decision variables are selected from design parameters according to their impact on objective function. In this paper six parameters are selected as decision variables that include the output power of Microturbine, the number of micro turbines, the area of PV panels, yearly profit, initial cost and energy cost. The number of microturbines and area of PV panels should be optimized so that the system can be supplied the heat and power with high reliability, also the cost of energy in the system must be minimized.

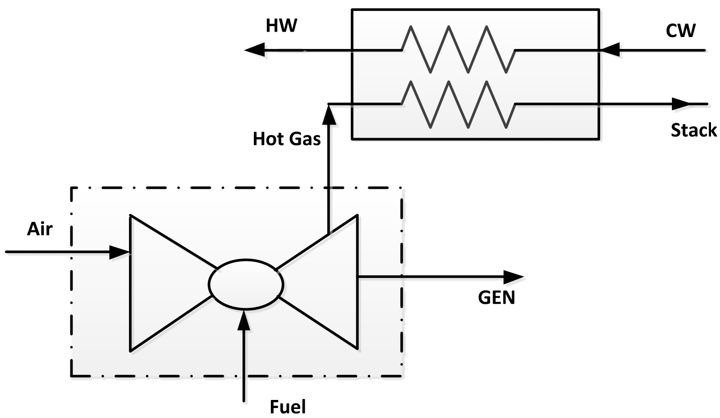

Figure 4 The schematic diagram of Microturbine [24]

For this purpose, an objective function is considered which it consists of two main parts. The first part includes the costs of power and heat generation by conventional systems and the second parts describes the cost of generation by micro-CHP system. This later is comprised of several parts. The objective function is formulated as below:

$$\mathrm{AP}=\sum_{nm=1}^{12}\left[\overbrace{\left(\mathrm{E_{req}}c_{e,buy}+\mathrm{H_{req}}c_{h,b}\right)}^{\substack{\text{the cost of conventional generation}\\ \text{of electricity and heat}}}-\left(\overbrace{\mathrm{E_{CHP}}c_e+\mathrm{H_{CHP}}c_h}^{\substack{\text{the cost of electricity and}\\ \text{heat by CHP system}}}+\overbrace{\langle \mathrm{E_{req}}-\mathrm{E_{CHP}}\rangle c_{pv}}^{\substack{\text{the cost of supply}\\ \text{Electricity Deficit by PV panel}}}+\overbrace{\langle \mathrm{H_{req}}-\mathrm{H_{CHP}}\rangle c_{h,bb}}^{\substack{\text{the cost of generation}\\ \text{heat Deficit}}}\right)\right]t_{nh} \tag{5}$$

In the above equation, E_{req} and H_{req} describe the required power and heat respectively. E_{CHP} and H_{CHP} represent the generated power and heat by CHP system, $c_{e,buy}$, c_e and c_{pv} , also show the cost of buying electricity from the grid, the price of generated electricity bye CHP and PV panels respectively. The $c_{h,b}$ and $c_{h,bb}$ parameters describes cost of heat generated by the boiler in a conventional energy systems and price of heat generation by backup boiler in CHP systems. The value of n is determined according to the required thermal and power during the year. Since the required heat and power load were given monthly in this paper, then t_{nh} is the number of hours of running the system in a month. The schematic diagram of the boiler and also constant input values to compute the objective function are shown in Figure (5) and Table (3) respectively.

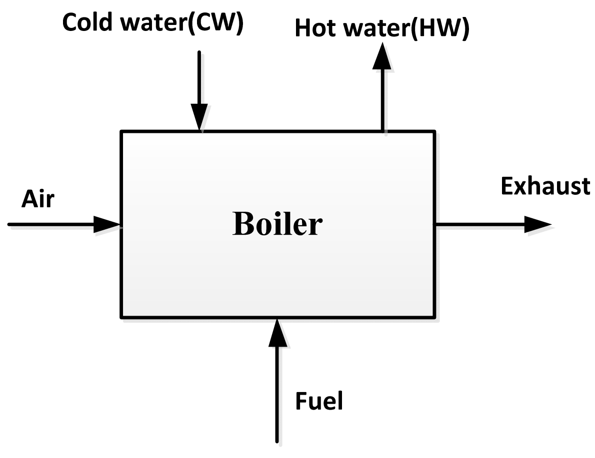

Figure 5 Schematic diagram of boiler

Table 3 The values of input parameters for objective function [25]

$\varphi_{e,buy}(\frac{\$}{Kwh})$	0.1	Hr (hour)	7446
$c_f(\frac{\$}{Kwh})$	0.02	$\eta_{GEN}(\%)$ S(%)	95 10
Ir (%)	10	ΔP_{HR}	0.05
N (year)	20	$T_0(°C)$	15
μ	1.06	P_0(kpa)	100.13

The required equation to calculate investment and generated cost of system are shown in Table (4) [26, 27].

Parameter c_{pv} represents the cost of electric power generated by PV panels. This cost can be obtained by the below equation [28]:

$$c_{pv} = \frac{\text{Installation Cost}(\$)}{\text{power output}(kwh)} \tag{6}$$

$$\text{nstallation Cost} = \text{capital cost}\left(\frac{\$}{m^2}\right) \times \text{Station Capacity}(m^2) \tag{7}$$

$$\text{Capital Cost }\left(\frac{\$}{m^2}\right) = \text{module Cost}\left(\frac{\$}{w_p}\right) \times \eta \times 1000 \tag{8}$$

Station Capacity is the required area of PV panel to supply the deficit system power. Another important factor in system design is payback period which can be obtained using the following equation [29].

$$Z - \sum_{t=1}^{n} YP_t(1 + ir)^{-t} \leq 0 \tag{9}$$

Where Z is defining the investment costs of all equipment in CHP system, ir is the interest rate and YP is the yearly profit. Due to the yearly profit, the payback period is equal to the smallest value of n that satisfies Eq. (9).

Table 4 The equation of cost parameters for proposed system

cost of generated power in microturbin	$C_e = \frac{C_{10}\dot{E}_{10}}{\dot{E}_e - \dot{E}_{sur}} + \frac{CRF.\mu.Z_{GEN}}{hr \times (\dot{E}_e - \dot{E}_{sur})}$	microturbin investment cost	$Z_{MT} = 4071 \times W^{0.7}$
generator investment cost	$Z_{GEN} = 60 \times W^{0.95}$	price of generated heat	$C_h = \frac{C_g\dot{E}_g}{\dot{E}_h - \dot{E}_C} + \frac{CRF.\mu.Z_{HE}}{hr(\dot{E}_h - \dot{E}_C)}$
Capital Return Factor	$CRF = \frac{ir\,(1 + ir)^n}{(1 + ir)^n - 1} - \frac{ir \times S}{(1 + ir)^n - 1}$	price of heat production by boiler in the conventional system	
boiler investment cost	$Z_B = 250\,H^{0.87}$	price of mechanical power of microturbin	$C_m = \frac{C_f\dot{E}_f - C_g\dot{E}_g}{\dot{E}_m} + \frac{CRF.\mu.Z_{MT}}{hr \times \dot{E}_m}$

5 LUS based PSO algorithm

In order to determine the optimal design parameters for the hybrid solar micro-CHP system described in previous sections, an intelligent optimization method based on PSO algorithm and LUS technique is developed. In the subsequent sections, details of the proposed optimization algorithm are introduced.

5.1 PSO algorithm

PSO is a population-based optimization algorithm that consists of NP particles $X_i, i = 1,2,\dots,NP$. Each of these particles is a possible solution of the problem. In the variable space, each particle has a position identified by $X_i = [x_{i1}, x_{i2}, \dots, x_{id}]$ and a velocity identified by $V_i = [v_{i1}, v_{i2}, \dots, xv_{id}]$. The position and velocity of Particles are originally initialized in a uniform random manner throughout the search space. Then, the position X_i and the velocity V_i are updated by the best position encountered by the particle so far and the best position found by $Pbest_i = [pbest_{i1}, pbest_{i2}, \dots, pbest_{id}]$ encountered by the particle so far and the best position $Gbest = [gbest_1, gbest_2, \dots, gbest_d]$ found by the entire population of particles according to the following equations [30].

$$V_i(t+1) = w.V_i(t) + c_1 r_1 \left(Pbest_i - X_i(t)\right) + c_2 r_2 \left(Gbest - X_i(t)\right) \tag{10}$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{11}$$

where c_1 and c_2 are two learning factors which control the influence of the social and cognitive behaviors, $r_1$and r_2 are random numbers within the range $[0,1]$, and w is the inertia weight, which ensures the convergence of the PSO algorithm and is achieved properly. The Pseudocode of PSO algorithm is illustrated in Figure (6).
Although PSO algorithm has been applied successfully in solving many difficult optimization problems, it also has difficulties in keeping balance between exploration and exploitation when solving complex optimization problems. Exploration and exploitation are two important concepts in any optimization algorithm. Exploration is the ability of the algorithm to search for new solution far from the current solution in the search space.

Objective function $F(X_i)$, $X_i = [x_{i1}, x_{i2}, \dots, x_{id}]$
Step 1: Initialization.
Set the generation counter $t = 1$
Initialize a population of NP particles with random position $X_i(t)$ in a given search space, and random
velocities $V_i(t)$
Set $Pbest_i = X_i(t)$
Find global best Gbest at $t = 1$
Step 2: While the termination criteria is not satisfied **or** t <Max number of iterations **do**
Calculate new velocity and position of each particle via (10) and (11)
Evaluate the new fitness
if $F(X_i(t+1) < F(Pbest_i)$
$Pbest_i = X_i(t+1)$
$F(Pbest_i) = F(X_i(t+1)$
Rank the particles and find the current best bat Gbest
$t = t + 1$
Step 3: end while

Figure 6 The Pseudocode of original PSO algorithm

Exploitation is to search the vicinity search area nearby the current solution, something like local search. Successful implementation of PSO algorithm depends on proper trade-off between exploration and exploitation. Finding the control parameters of an optimization algorithm that could handle both exploitation and exploration is challenging because they are two different objectives.

The control parameters which impact the performance of PSO are learning factors c_1 and c_2, inertia weight w and population size NP. As there is no fixed rule and agreement in the literature on how to optimally select PSO parameters, to overcome above difficulties, and also avoid the tuning of parameters by trial-and-error procedure, the LUS method described in next section is used in this paper for finding the optimal values of PSO parameters.

5.2 LUS Algorithm

LUS algorithm is a local search algorithm which is widely applied to many simple optimization problems because it is robust and gradient free. It starts with a candidate solution and then iteratively moves to a neighbor solution. Performance of the intelligent optimization algorithm depends on their controlling parameter. Proper selection of these parameters plays an important role in the convergence characteristic of the algorithm. For example the controlling parameters in PSO are w, C_1, C_2 and NP, LUS technique can be used to find the optimal values of these parameters. For each of controlling parameters, LUS starts with a search range then decreases it iteratively until the optimal value is reached. Search range is defined as $D = (D_1, D_2, \dots, D_n)$, where n is the number of controlling parameters that must be optimized [31]. For example in this paper, as there are four tuning parameters (i.e. w, C_1, C_2 and NP), n is equal to 4.

The initial search range of each parameters is defined based on upper and lower boundary $b_{up} = (b_{up_1}, b_{up_2}, \dots, b_{up_n})$ and $b_{low} = (b_{low_1}, b_{low_2}, \dots, b_{low_n})$.

$$D_i = b_{up,i} - b_{down,i} \tag{12}$$

First, the optimal solution s is defined as $s = (s_1, s_2, \dots, s_n)$. Then at the first iteration $t = 0$, the values of each parameters are initialized randomly as the following [32]:

$$s \sim U(b_{low}, b_{up}) \tag{13}$$

After that, the objective function is evaluated for s values. Then, a new set of controlling parameters s_{new} is calculated using the bellow equation:

$$s_{new} = s + a \tag{14}$$

where $a = (a_1, a_2, \dots, a_n)$, is a random values within the search $(-D, D)$. Now, s_{new} is used to determine a new objective function value. If this new objective function value is better than the previous one, s is changed to $s = s_{new}$, otherwise, as shown below, the search range D is decreased for all dimensions by multiplying with a factor q to determine a new set of parameters s_{new}.

$$D = qD \tag{15}$$

The decrease factor q is defined as the following equation.

$$q = 2^{-\beta/n} \tag{16}$$

Where β is a user defined behavior parameter and n is a number of controlling parameters. The above mentioned process is repeated until the maximal number of iterations maxEval for LUS algorithm is reached, or until accuracy for generated set of weights is 100% [34]. More details about this algorithm can be found in Ref. [34].

6 Results and Discussion

In this section the adequacy of the proposed LUS based PSO approach has been evaluated in the hybrid solar and micro-CHP system described in previous sections. The upper and lower limits of controlling parameters are chosen as follows:

$$NP \in \{1,2,\dots,200\},\ \ w \in [0,1], C_1 \in [0,2], C_2 \in [0,2].$$

Then LUS is trying to find the optimal values of these parameters. Using the above settings, the best parameters found for the algorithm are as follows:

$$NP = 27,\ w = 0.63, C_1 = 0.86, C_2 = 1.14$$

To validate the modeling and optimization results, the prime mover specifications at nominal power is extracted from the equipment catalogues. In addition the operational specifications of running equipment at partial load are collected. The maximum 8.5% difference is observed between the numerical values obtained from the mentioned references and the proposed relations in this study. Using the conventional CHP system, the total energy cost (EC) for buying the power load and heat by considering the inflation ratio 4%, is calculated 69437$/year. These values for the proposed hybrid system are illustrated in Tables (5)-(6). Moreover, the Yearly Profit (YP), payback periods, the area of PV panels and the type and number of microturbins and their output powers are also shown in this Table. Comparison between proposed hybrid energy system and conventional system with respect to EC data shows that the cost of generated heat and power by CHP system is much lower than conventional system. As can be seen, the hybrid solar and micro-CHP system reduces the energy cost in comparison to conventional CHP system.

Table 5 Results: Optimal values of design parameters for CHP using PSO_LUS, DE and GA

System Type	Power (Kw)			Number of Microturbines			Energy Cost (1000$/year)			YP (1000$/year)		
	PSO_LUS	DE	GA	PSO_LUS	DE	GA	PSO_LUS	DE	GA	PSO_LUS	DE	GA
A	30	30	30	4	4	4	50.21	55.97	58.73	26.92	24.94	24.33
B	60	60	60	2	2	2	48.01	56.87	56.85	29.91	26.89	24.92
C	70	70	70	2	3	2	51.98	55.88	54.45	27.14	2486	24.68
D	75	75	75	2	3	3	53.82	61.48	60.42	25.16	23.16	22.43
E	80	80	80	2	2	2	48.39	54.05	52.51	27.75	26.77	26.45
F	100	100	100	1	1	1	54.02	57.88	55.85	25.93	23.92	23.53

Table 6 Results: Optimal values of design parameters for PV using PSO_LUS, DE and GA

System Type	Power (Kw)			Installation Cost (1000$/year)			Payback Period (Years)			PV Area (m^2)		
	PSO_LUS	DE	GA	PSO_LUS	DE	GA	PSO_LUS	DE	GA	PSO_LUS	DE	GA
A	30	30	30	31.47	34.23	32.62	3	3	3	59.69	59.69	59.69
B	60	60	60	28.11	29.02	28.62	2	3	3	59.69	59.69	59.69
C	70	70	70	28.98	29.97	29.69	3	4	4	45.69	45.69	45.69
D	75	75	75	31.13	33.27	32.75	3	4	4	38.68	38.68	38.68
E	80	80	80	30.54	32.47	31.86	3	3	3	31.68	31.68	31.68
F	100	100	100	20.85	22.94	23.18	2	2	2	75.41	75.41	75.41

To validate the performance and effectiveness of the LUS based PSO algorithm, the simulation has been performed and the results are compared to those of other algorithms including Differential evolution (DE) algorithm and genetic algorithm (GA), as listed in Tables (5)-(6). It is observed that the performance of LUS based PSO is better than DE and GA algorithms in terms of convergence as well as diversity. It is worth mentioned that the initial population of LUS based PSO is 27; however, this parameter for other algorithms is higher for achieving proper convergence.

Hence, it is determined that the proposed optimization algorithm, as compared with other optimization methods, can search the feasible space more effectively and reach the global optimum with lower number of objective function evaluation. The convergence behavior of three algorithms for one of the best runs is shown in Figure (7). This figure indicates that the convergence speed and accuracy in LUS based PSO are significantly higher than the DE and GA algorithms. In this figure, the cost value function is normalized, such that the cost value always lies in the range [0, 1]. In order to select system based on Yearly Profit, it is required to compare the YP shown in Tables and choose system with the highest YP value. Results of this comparing are shown in Figure (8). It is clear from this figure that two B type (60ICHP) microturbines have the highest Yearly Profit for proposed heat and power load. In order to select system based on payback period, results show that although the B type microturbin has the highest YP, the payback period for this system is not the shortest one. The shortest payback period belongs to F and B types with 2 years payback periods. Since the payback period of B and F systems are close and difference in Yearly Profit of B and F systems are significant, it is concluded that B type microturbines are acceptable system for the proposed operation loads.

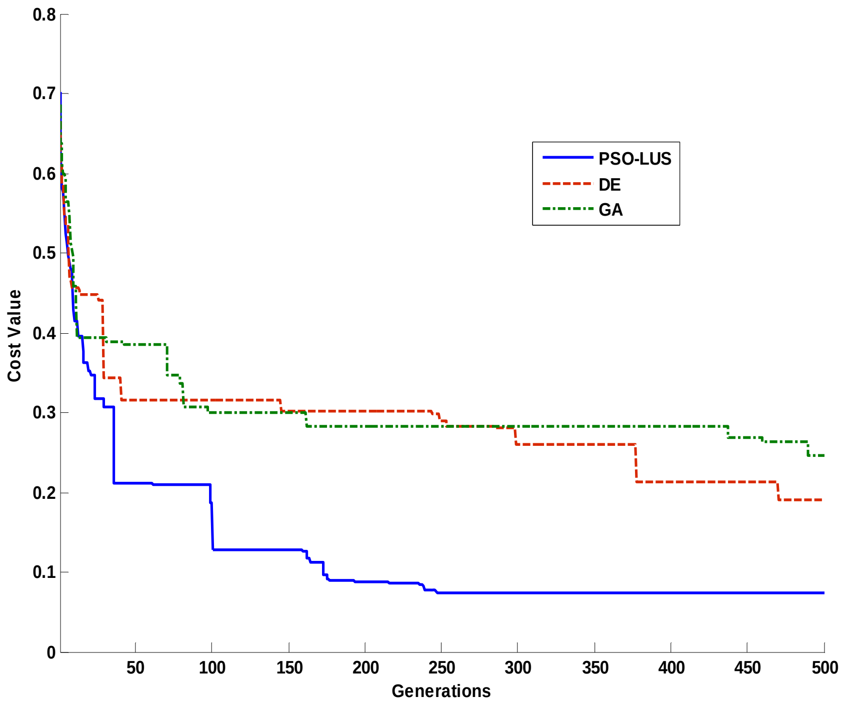

Figure 7 Convergence characteristics for optimization algorithms

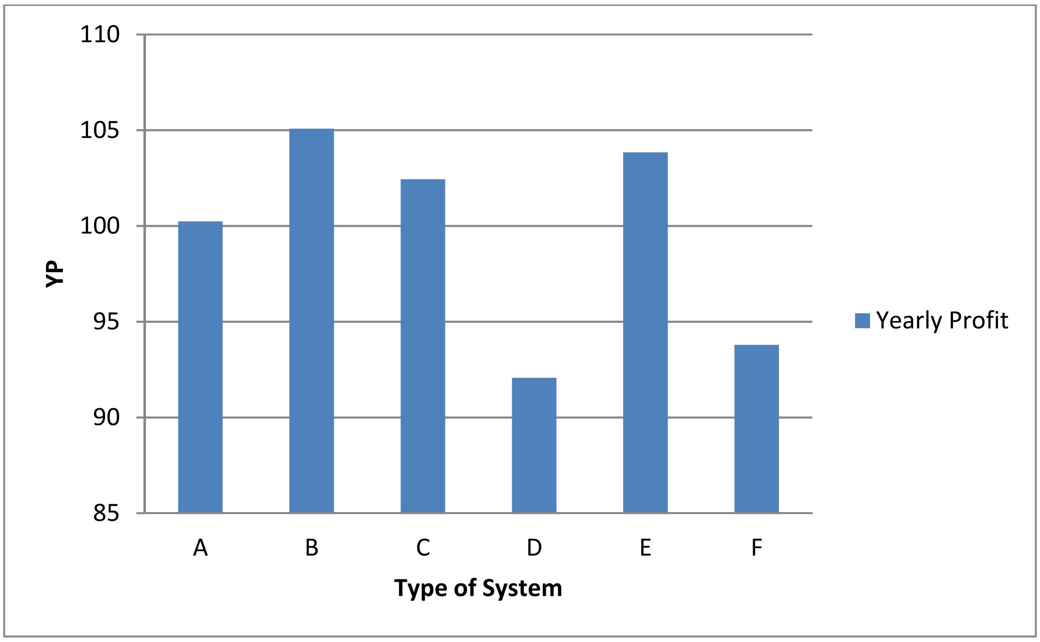

Figure 8 Comparison of YP for different type of microturbins

To verify the optimum results of the PSO based on LUS algorithm and to ensure reaching the global optimum in each optimization run, the optimization problem is performed 20 times for the same input and the values of relative standard deviation (RSD) are computed, which is defined as follows [35]:

$$\mathrm{RSD}(\%) = \frac{\sqrt{\sum_{i=1}^{N} \frac{1}{N-1}\left(\mathrm{AP}_{S_i} - \mathrm{AP}_{ave}\right)^2}}{\mathrm{AP}_{ave}} \times 100$$

Where N and AP_{ave} are the number of runs (20 runs) and the average value of annual profit (in 20 runs), respectively. The value of RSD is 0.73% which proves that the proposed optimization algorithm is a robust optimization technique. The term robust denotes the ability of the algorithm in finding the global optimum, or a near-optimal point, for an optimization problem.

7 Conclusion

This paper proposed a hybrid system using conventional CHP and solar photovoltaic panels to supply the shortage of power in conventional CHP systems. The microturbines were selected as prime movers because they are easy to carry and they have lower weight and lower co_2 emissions. For economic optimization of the CHP systems, two objective functions annual profit and total cost rate were introduced to select the type and the number of prime mover and also the area of photovoltaic panels. The proposed hybrid system (CHP+solar) was optimally designed using LUS based PSO technique and its performance was compared in terms of convergence and optimization of objectives with GA and DE algorithms. These results can be used as guidance in the planning stage of cogeneration system to make better choices between various options and scenarios. Also, it may be used for engineers and planners to choose balancing solutions based on the sustainability economy of the system.

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Nomenclatures

E_e	electrical energy
E_{hW}	thermal energy of domestic hot water
E_{req}	required power
E_{CHP}	generated power by CHP system
$c_{h,b}$	cost of heat generated by the boiler in a conventional energy systems
$\dot{E}_C$	incoming cold water to the heat exchanger
t_{nh}	number of hours of running the system in a month
$\dot{m}_f$	flow rate of fuel
H_{req}	required Heat
Z	investment cost
h	enthalpy
E_{hG}	thermal energy of hot gas
E_f	fuel energy
H_{req}	required heat
$c_{h,bb}$	price of heat generation by backup boiler in CHP systems
H_{CHP}	generated heat by CHP system
Z_{HE}	heat exchanger investment cost
LHV	Low Heating Value of fuel
E_{req}	required power
$c_{e,buy}$	cost of buying electricity
c_{pv}	cost of electric power generated by PV panels
$\dot{E}_f$	fuel energy